

International Space Station Major Constituent Analyzer On-orbit Performance

Ben D. Gardner¹ and Phillip M. Erwin²
UTC Aerospace Systems, Pomona, California, 91767

Tamara Cougar³
The Boeing Company, Pasadena, Texas, 77059

and

BettyLynn Ulrich⁴
NASA Johnson Space Center, Houston, Texas, 77058

The Major Constituent Analyzer (MCA) is a mass spectrometer based system that measures the major atmospheric constituents on the International Space Station. A number of limited-life components require periodic change-out, including the ORU 02 analyzer and the ORU 08 Verification Gas Assembly. The most recent ORU 02 and ORU 08 assemblies in the LAB MCA are operating nominally. For ORU 02, the ion source filaments and ion pump lifetime continue to be key determinants of MCA performance. Finally, the Node 3 MCA is being brought to an operational configuration.

Nomenclature

AR = Atmosphere Revitalization
CH₄ = methane
CO₂ = carbon dioxide
CSCI = Computer Software Configuration Item
ECV = electrometer correction value
H₂ = hydrogen
H₂O = water
ISS = International Space Station
mA = milliamp
MCA = Major Constituent Analyzer
N₂ = nitrogen
NH₃ = ammonia
O₂ = oxygen
ORU = On-orbit Replaceable Unit
S/N = serial number
μA = microamp
VGA = Verification Gas Assembly

¹ Project Engineer, UTC Aerospace Systems, 2771 N. Garey Ave., Pomona, California 91767

² Software Engineer, UTC Aerospace Systems, 2771 N. Garey Ave., Pomona, California 91767

³ Mechanical Systems Design and Analysis Engineer, Environmental Control and Life Support Systems, The Boeing Company, 3700 Bay Area Boulevard, Pasadena, Texas 77058/HB2-30

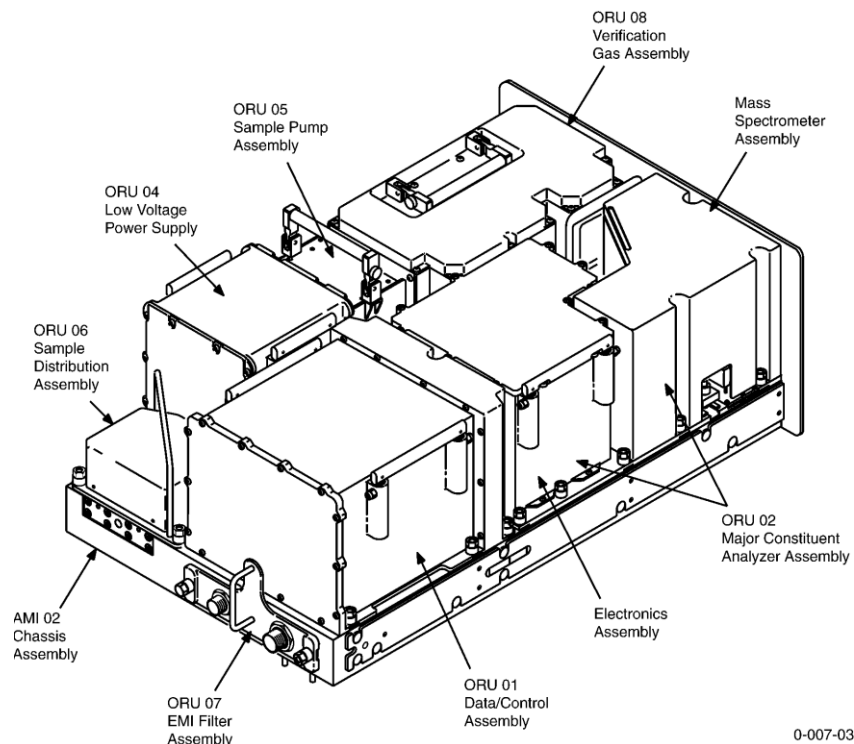
⁴ Atmosphere Revitalization Subsystem Manager, EC6 ISS ECLSS, NASA Johnson Space Center, 2010 NASA Boulevard, Houston, Texas 77058

I. Introduction

THE Major Constituent Analyzer (MCA) is a mass-spectrometer-based system designed to monitor six major atmosphere constituents: nitrogen (N_2), oxygen (O_2), carbon dioxide (CO_2), methane (CH_4), hydrogen (H_2) and water vapor (H_2O) in the atmosphere of the International Space Station (ISS). It is the primary resource for ensuring that the (O_2) and (CO_2) levels in the ISS atmosphere are maintained at safe levels, and the (N_2) partial pressure reading is used to monitor the ISS for cabin air leakage.

The MCA, shown in Figure 1, is designed as a set of seven On-orbit Replaceable Units (ORUs) that can be serviced or replaced individually in response to periodic maintenance requirements. The modular design approach optimizes logistical support to provide service on limited-life components without having to change out the entire MCA. Of these ORUs, ORU 08 (Verification Gas Assembly) and ORU 02 (Mass Spectrometer Analyzer) are the more commonly replaced subsystems. ORU 02 is the mass spectrometer analyzer that forms the technological core of the MCA. It is comprised of a gas inlet, an ion source, a single-focusing magnetic sector mass spectrometer, six spatially arrayed ion detection electrometers, associated electronics, and a 4 L/sec ion pump. The primary life-limiting items include the ion source filament (of which there are two) and the ion pump. Considerable attention is being paid to determining the factors limiting both the ion pump and ion source lifetimes, as has been described previously¹⁻⁶. To date, the ion pump has been the driving issue for ORU 02 periodic replacement; however, operation of the ion pump at a lower voltage, implemented under CR10773A, is expected to increase ion pump lifetime.

This paper reports the lifetime history and recent performance characteristics of the ORU 02 used in service over this past year, as well as the performance of ORU 08. Review of performance data from recent ORU 02s suggests that ORU 02 design changes have been successful in increasing ORU 02 life. Also described is the possibility of adapting the MCA to detect ammonia (NH_3).



0-007-03

Figure 1: Major Constituent Analyzer

II. On-orbit Activities

A. MCA Transitions On Station

MCA on-orbit activity was last reported at the 2016 ICES Conference¹. The MCA in ISS Node 3 is installed in Air Revitalization Rack #2 (AR2). ORU 02 F0003 operated from September 2013 to October 12, 2016. This ORU 02 operated for approximately 1100 days before an ion pump short required the unit to be replaced. This was a new record for ORU 02 longevity on orbit. This ORU 02 was removed in January, 2017, and replaced with ORU 02 F0001, which is in the process of being stabilized on-orbit.

In December, 2014, ORU 01 F0002, ORU 02 F0007, and ORU 08 F0003 were installed into the US Lab MCA (AR1) to complete the MCA and provide a second system on orbit for the first time since 2011. ORU 01 F0002 contains the latest firmware, MCA CSCI 4.25, with added capabilities for extending ORU 08 life and improvements to H₂O measurement accuracy. At completion of the power-up initialization sequence, the Lab MCA transitioned to FAIL state. Analysis of telemetry indicated that ORU 01 was functioning properly, but that ORU 02 F0007 was not operational. In September, 2016, ORU 02 F0007 was removed and replaced with ORU 02 F0006. This ORU 02 activated successfully and is now operating nominally. The first full calibration on orbit of ORU 02 F0006 was performed on October 4, 2016. As indicated above, ORU 02 F0003 was still operating in the Node 3 MCA at that time and approximately one week of simultaneous operation of two MCAs occurred. Some data for comparison of the two MCAs was obtained during that week.

III. ORU 02 Performance Metrics

A. Calibration Stability

ORU 02 analytical stability can be evaluated by tracking the calibration over time. Each ORU 02 is calibrated on the ground to determine its gain characteristics for the detection of each of the major atmospheric constituents. The calibration is based on the responses to gas mixtures of known, very accurately controlled compositions. The resulting calibration values are then programmed into the ORU 02 prior to its protoflight acceptance testing. It is known that the calibration values can change slightly over time for various reasons. Consequently, once on orbit, the ORU 02 calibration is adjusted periodically using a verification gas mixture (a.k.a. calibration gas or cal gas). This involves measuring the background offset of each electrometer and determining a gain adjustment factor, the Electrometer Correction Value (ECV) for each of the six atmosphere constituents measured by the MCA. Ideally, if the performance doesn't change, each ECV should stay at or close to a value of 1.0000. Any change in gain value is compensated for by taking the ratio of the expected response (partial pressure of each calibration gas constituent) to the measured response (MCA calculated partial pressures for each constituent) and using that value for the computational correction factor — the ECV. The ECVs are used to adjust the result of MCA partial pressure calculations so that the MCA readout remains calibrated against the known composition of the calibration gas mixture. Experience has shown that the absolute value of ECVs may change with time, but the critical factor is that the ECVs do not change significantly with respect to each other. For trending purposes, the ECVs are “normalized” (i.e., each ECV is divided by the weighted ECV of the three most abundant gases (N₂, O₂ and CO₂)).

B. Ion Pump Current Trending

The ORU 02 ion pump is responsible for maintaining the operational vacuum level of the analyzer, and its degradation over time is historically the primary factor that limits the useful longevity of an ORU 02. Ion pump current is a measure of the gas pumping load and, therefore, analyzer pressure. It is typically 60 to 100 μ A at the start of its operating life. In the absence of any parasitic shunt currents that occur as the pump ages, a high ion pump current is indicative of a high pressure internal to the analyzer. The vacuum level of the ORU 02 analyzer must be maintained low enough to prevent the ion source filaments from burning out too quickly, so the MCA is configured to automatically ‘safe’ the analyzer and protect the filaments when the ion pump current reaches 370 μ A. At this point, the MCA generates an error code and goes to FAIL state (i.e., shuts down). The ion pump current is a function of both the gas load and the effects of ion pump wear. Typically, the base ion pump current increases over time and the margin between this current and 370 μ A is reduced, eventually leading to ion pump end of life.

C. Filament Current Trending

The ORU 02 ion source contains two filaments which generate the electrons used to create electron ionization (EI) derived ions from the gas molecules. ORU 02 normally uses Filament 1 until it is nearly completely consumed or fails, at which point MCA directs the use of the backup filament, Filament 2. Filament performance is monitored using

a filament current sensor upstream in the filament control circuitry, reading the current of the primary of a transformer. The filament current sensor reading (FCS01) normally starts at a reading of 120–150 mA when a filament is new (~135 mA is typical), and gradually decreases over time. The slope of a plot of FCS01 gradually becomes more negative until the value reaches about 100 mA, after which it rapidly becomes steeper and the filament fails shortly thereafter. On-orbit practice is to switch from Filament 1 to Filament 2 when FCS01 decreases to about 108 mA, so that Filament 1 can be retained as a backup to Filament 2 should that filament fail during an essential activity on orbit.

IV. Historical ORU 02 Performance

The historical performances of the ORU 02s that have been used on orbit are listed in Table 1.

Table 1: ORU 02 On-Orbit Usage

ORU 02 Serial No.	Activated	Deactivated	MCA Serial No.	Comments
Q0001	2/12/01	6/23/01	Q0001	Insufficient operating time to accumulate life data.
F0004	6/23/01	4/25/02	F0001	
F0003	9/1/02	9/29/04	F0001	Failed (end of life) with high ion pump current in September 2003. Used in Life Extending Mode until removal in September 2004.
F0002	9/30/04	2/16/06	F0001	Replaced due to increasing frequency of bad zero calibrations due to ion pump noise.
F0001	3/6/06	12/28/08	F0001	Operated 33 months. Removed before end of life to minimize impact to on-orbit operations.
F0004	1/2/09	9/22/09	F0001	Operated 9 months. Had one shutdown due to high ion pump current spike. Was replaced before failure in order to minimize impact to operations.
Q0001	9/25/09	1/23/12	Q0001	Operated 19 months on orbit. High ion pump current. Replaced prior to end of life.
F0003	9/13/10	10/8/10	F0001	Premature failure of Filament #1. Operated 9/13/10 – 10/8/10 w/ new ORU 01 F0001 and CSCI 4.24.
	5/13/11	6/6/11		Operated 5/13/11–6/6/11 w/ ORU 01 Q0001 and CSCI 4.18. Filament 2 failure.
F0001	7/6/11	7/16/11	F0001	Premature filament failures.
F0005	1/28/12	8/30/13	Q0001	Operated 19 months on orbit. End of life replacement due to ion pump short.
F0003	9/13/13	10/12/2016	Q0001	Operated 37 months. Removed due to ion pump short.
F0007	12/24/2017	9/13/2016	F0001	Never operated on orbit. Possible connector problem.
F0006	9/13/2016	--	F0001	Operating normally in Lab MCA.
F0001	1/28/2017	--	Q0001	Operating in Node 3 MCA. A problem with Z-Axis deflection requires recalculation on the ground of electrometer backgrounds and constituent ECVs.
F0008				On orbit spare

V. Recent ORU 02 Performance

The performance lifetimes of ORU 02s have varied from less than a year to nearly 3 years. The primary failure mode has been the result of the ion pump reaching end of life, although several ORU 02s have been replaced earlier to accommodate other on-orbit activity. More recently, two ORU 02s were replaced due to ion source issues. It is expected that the implementation of modifications to the ion pump operation, as well as adjustments to initial ion source tuning will yield greater durability of future ORU 02s.

D. ORU 02 F0003

ORU 02 F0003 was installed in the Node 3 MCA on September 13, 2013. It was immediately pumped down and the ion pump activated. After three days, on September 16, ORU 02 F0003 was fully activated. The first on-orbit calibration of ORU 02 F0003 was performed on September 19, 2013. It was approved for improved accuracy operation 6 weeks later. The performance of ORU 02 F0003 was outstanding. No anomalous issues were reported, and performance characteristics supported the conclusion of this being the best of all ORU 02s flown thus far.

This ORU 02 failed on October 12, 2016, due to an ion pump short.

1. Analytical Stability

This ORU 02 performed very well analytically. A plot of normalized ECVs for CH₄, CO₂, H₂, N₂, and O₂ is shown in Figure 2. Although the legend lists H₂O, the H₂O values are off scale. Figure 3 includes H₂O ECVs using an expanded scale.

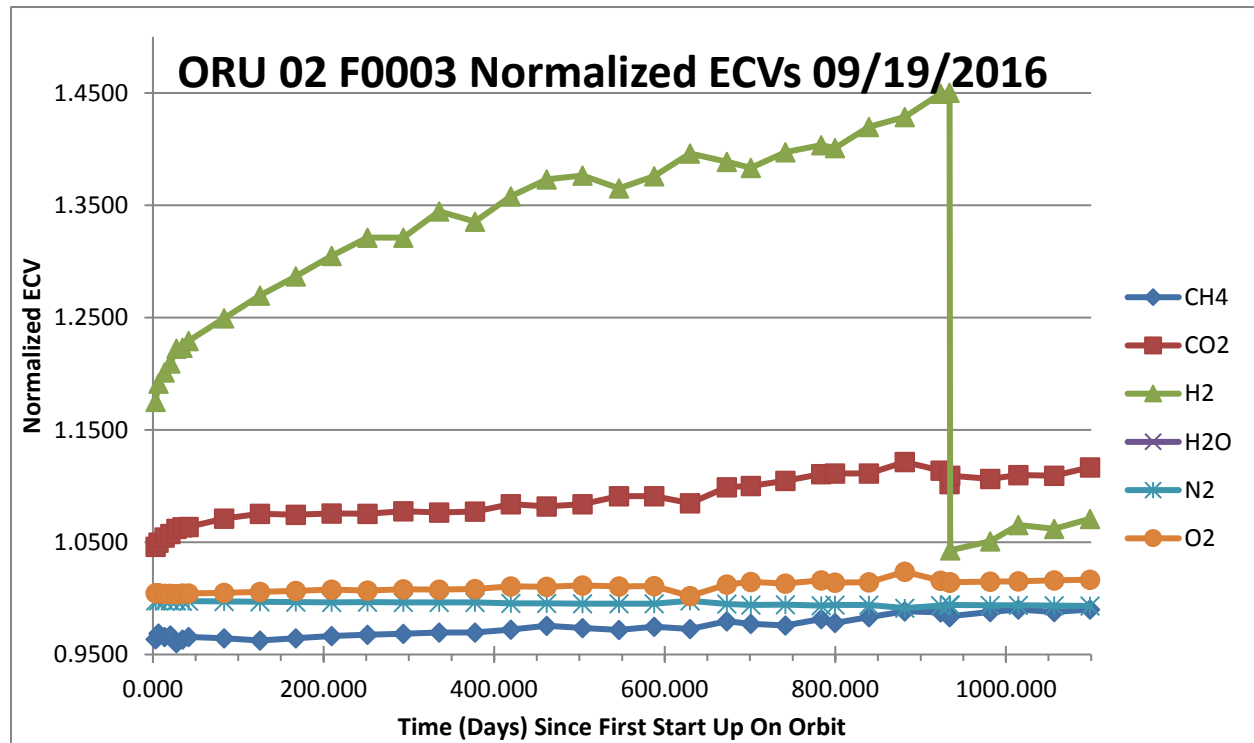


Figure 2: ORU 02 F0003 On-orbit ECVs

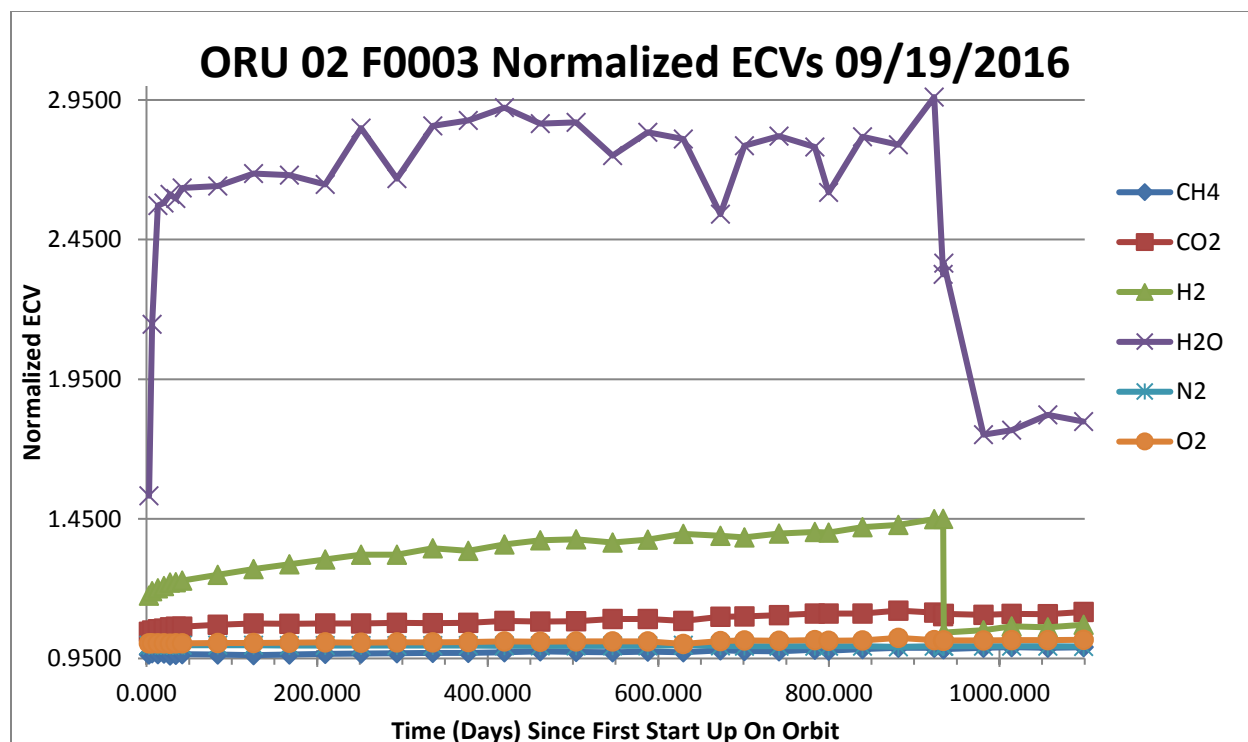


Figure 3: ORU 02 F0003 On-orbit ECVs Expanded Scale

The CH₄, CO₂, N₂, and O₂ ECVs were stable and instrument drift was consequently not a problem for these constituents.

The H₂ ECV rose approximately 24% in the first 133 weeks since initial instrument stabilization, which was approximately 1% during each 6-week interval between ECV calibrations. Since H₂ has a very small partial pressure, errors of this magnitude produce very small resulting errors in the partial pressure measurements. At approximately 133 weeks, a command was sent to the MCA that rescaled the H₂ ECV from about 1.45 to 1.04. This was done to avoid a firmware parameter limit. This accounts for the discontinuity of the H₂ ECV seen in the ECV figures.

The water ECV had the largest change between calibrations at approximately 8% worst case. For a typical ISS water partial pressure of approximately 10 Torr, an ECV change of this magnitude could lead to an error in water partial pressure of about 0.8 Torr. The calculation of partial pressures normalizes the partial pressures of all gases such that the total equals the total pressure in the compartment being sampled. Because of this, if one gas is erroneously increased by some magnitude, then other gases are reduced to compensate; if a gas constituent is erroneously decreased, then other constituents are increased to compensate. In this case, an error of -0.8 Torr in water would cause compensating errors of approximately +0.6 Torr in N₂ partial pressure and +0.2 Torr in O₂ partial pressure, for typical ISS atmosphere composition. Both of these side effects are not considered significant. The compensating errors for CH₄, H₂, and CO₂ are also insignificant. Note that Figure 3 shows a shift of the H₂O ECV from about 2.95 to 2.36 and then down to about 1.8. This change was due to the installation of new MCA firmware 4.25, which has an updated methodology for water calculation and calculates a different H₂O ECV.

The ECV data have never shown sufficient drift between calibrations to disturb the analytical performance of any ORU 02 operated on orbit. However, the sensitivity changes due to launch vibration, drift over time, and other causes are sufficient to send reported partial pressures out of expected accuracy if on-orbit calibrations are not performed.

2. Filament Performance

ORU 02 F0003 operated using Filament 1. Figure 4 shows the filament current sensor readings obtained during calibrations, with the data for other ORU 02s shown for comparison. The filament current curve extrapolated to a total lifetime of approximately 1200 days. This corresponded to the time at which the filament was expected to reach a

minimum 0.10 Amp current limit previously established. Filament 1 of this ORU 02 holds the duration record for on-orbit operation.

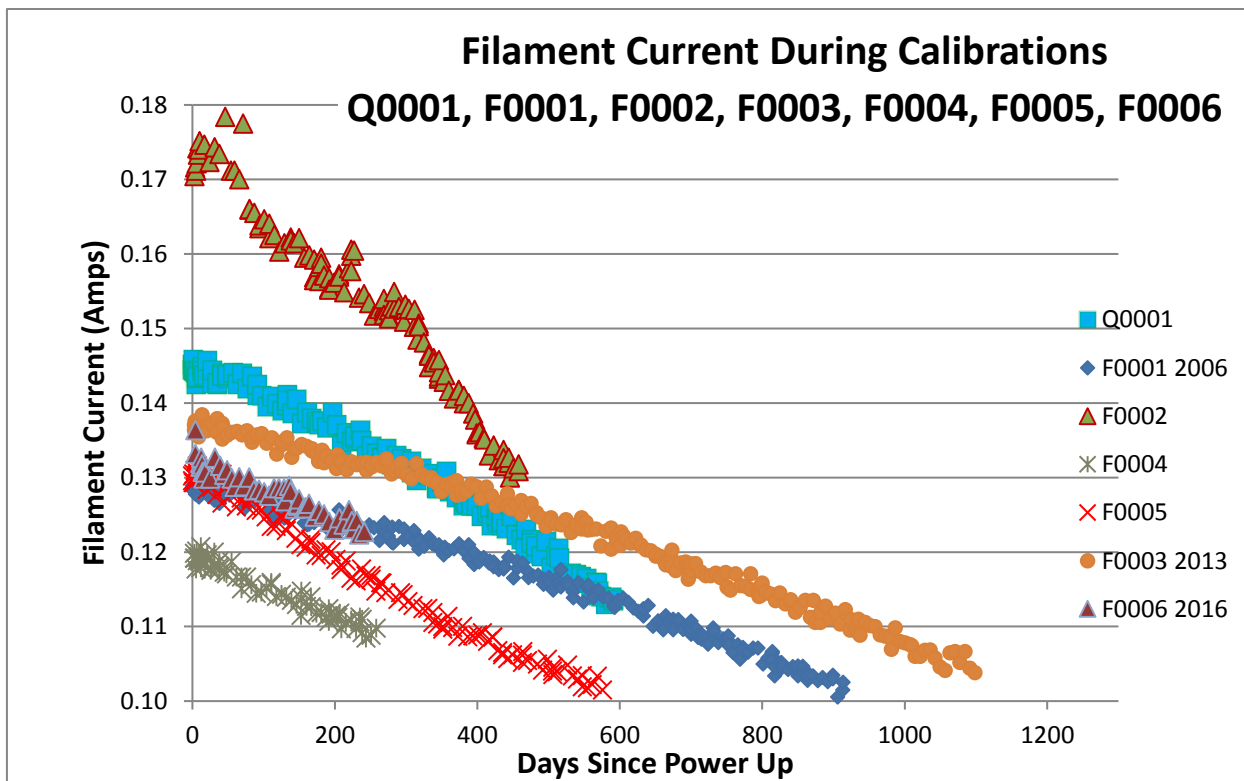


Figure 4: ORU 02 Filament 1 Current Sensor Readings

3. Ion Pump Performance

ORU 02 F0003 was the second ORU 02 on orbit with the reduced high voltage. The ion pump current of F0003 was more stable than for any previous ORU 02. Figure 5 shows the ion pump current measurements for F0003. The graph shows 10-minute averaged data. The ion pump current of F0003 showed a gradual rise of about 2 μ A per year. The ion pump current when the inlet valve was closed (i.e., no gas load) was only about 2 μ A. The ion pump current was only about two thirds of the current value of ORU 02 F0005, probably due to lower gas conductance of the inlet leak. Aided by the low operating current, this ion pump lasted longer than previous ion pumps. The ion pump was definitely the life-limiting item. There is every reason to believe the second filament could have operated F0003 for perhaps two more years.

Figure 5 also shows initial data for ORU 02 F0006. The ion pump current is the lowest seen so far, again probably due to the low conductance of the inlet leak. The low load on the ion pump gives the possibility of greater ion pump life.

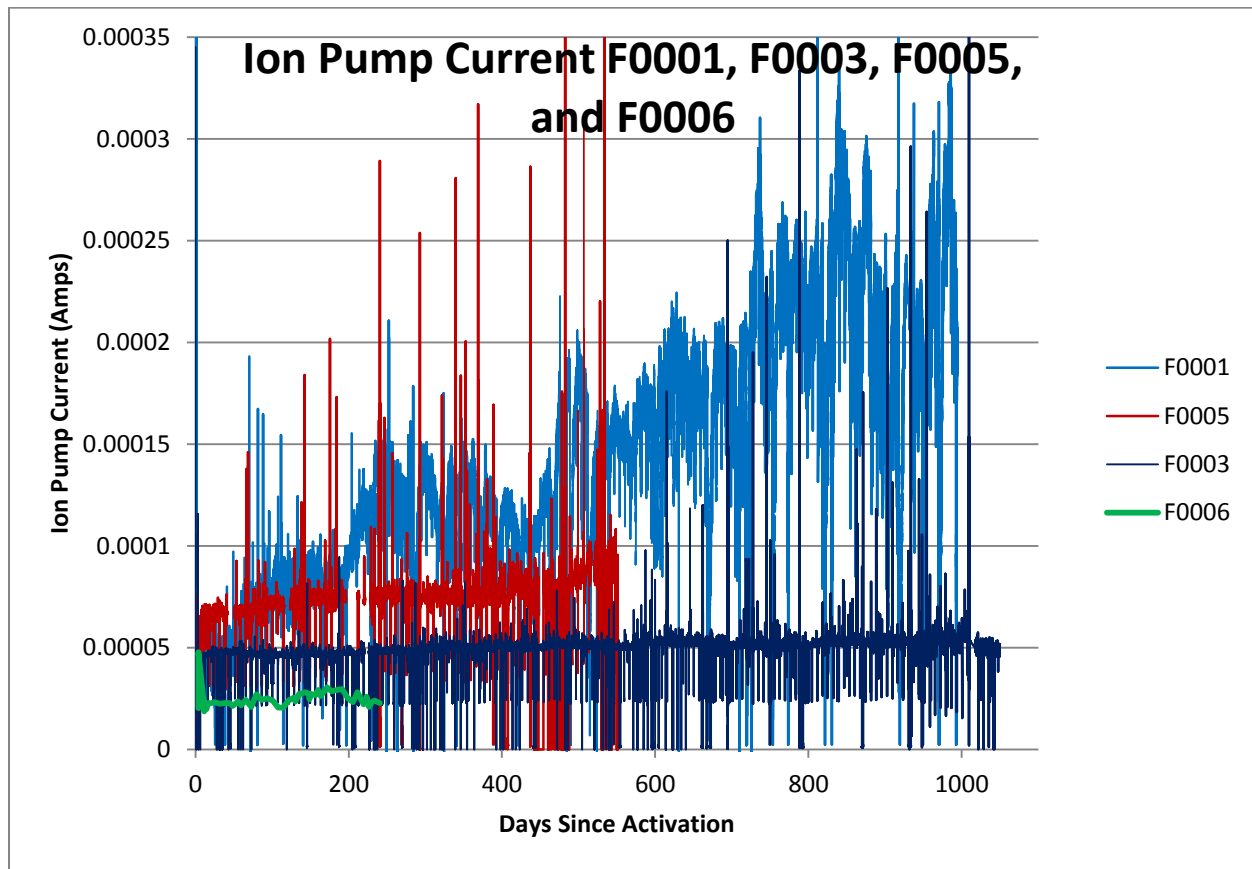


Figure 5: Ion Pump Current for ORU 02 F0001, F0005, F0003, and F0006.

VI. ORU 08 Performance

A. ORU 08 Q0001 Performance

ORU 08 Q0001 is the source of verification gas during Full Calibration procedures for the Node 3 MCA. While ORU 02 F0003 has been operated, the verification gas has been consumed at about 6 psi per Full Calibration, and Full Calibrations are normally performed about once per six weeks. The tank pressure reading is approximately 134 psia as 4/21/2017, and the ORU can supply gas until its pressure drops below 70 psia. At the current rate of consumption, this ORU 08 can supply the Node 3 MCA with verification gas for about sixty more weeks, until about June of 2018.

VII. Using MCA to monitor Ammonia

Recent events on ISS have motivated an examination of the extent to which MCA could be retasked to detect NH_3 . The external cooling system for ISS uses NH_3 as the thermal transport medium, and even a minor leak within ISS would pose a significant health hazard to the crew. Consequently, there is a desire to provide continuous monitoring at detection levels below the permissible exposure limit (PEL).

Testing of the MCA for NH_3 sensing capability is currently underway, and initial data acquired using the engineering Integration and Test Unit (ITU) has demonstrated that NH_3 monitoring with MCA is feasible. Additional testing to determine limits of detection will be performed in the near future.

VIII. US Lab MCA

The US Lab MCA had been inactive but was reactivated in December, 2014. The reactivation activity included installation of a new ORU 08, ORU 01 F0002, and ORU 02 F0007. The ORU 01 F0002 has new firmware, version 4.25, which had not previously been operated on orbit. The MCA powered up and established 1553B communication with the ISS Control and Data Handling system. The new firmware operated correctly.

During the reactivation activity, at completion of power up initialization, the MCA transitioned to FAIL state. Analysis of telemetry indicated that the new ORU 02 F0007 was not operational. The symptoms were consistent with a damaged wiring harness connector. The Lab MCA remained off until September, 2016, when ORU 02 F0007 was removed and replaced with ORU 02 F0006. This ORU 02 activated successfully and is now operating nominally. The first full calibration on orbit of ORU 02 F0006 was performed on October 4, 2016. The following figure shows the stability of the ECVs for ORU 02 F0006.

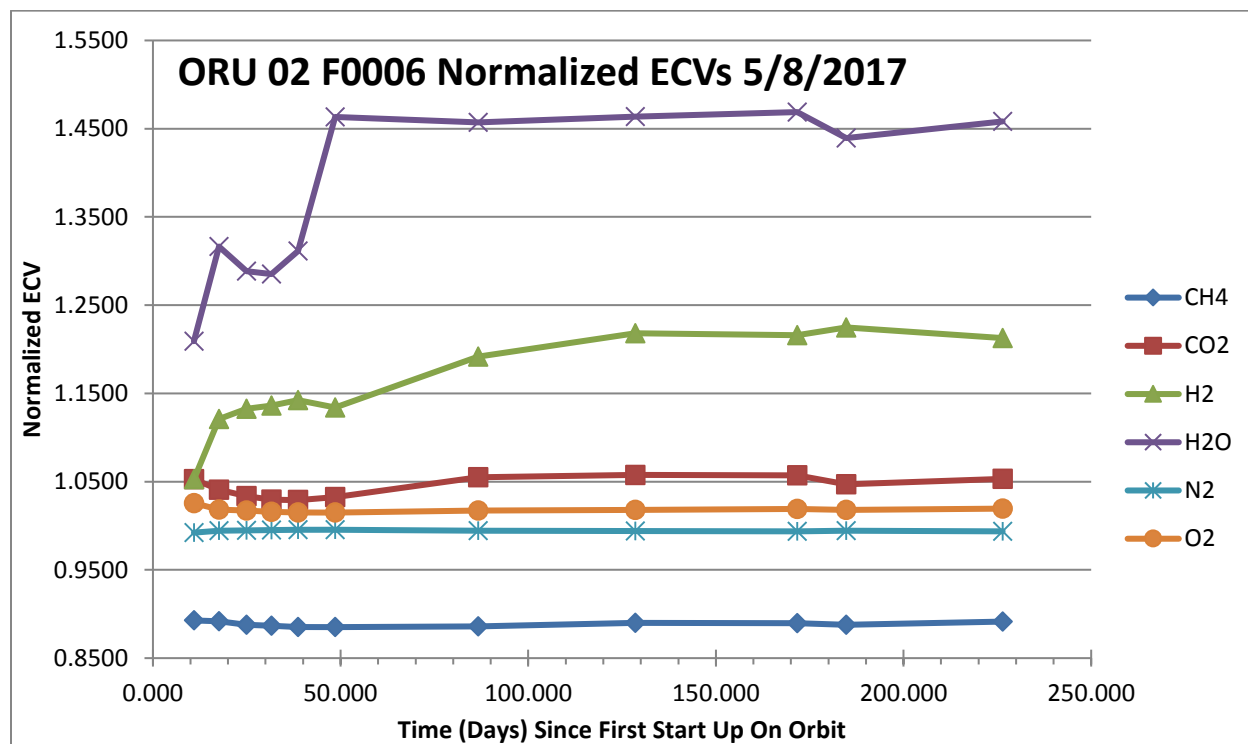


Figure 6: ORU 02 F0006 On-orbit ECVs

IX. Node 3 MCA ORU 01 R&R

ORU 01 is the subassembly that includes the processor, memory, 1553B communication interface, and most of the support electronics of the MCA. This includes electronics to measure the pressure transducers PT02 (ORU 06 manifold pressure), PT04 (verification gas supply line pressure), and PT05 (verification gas tank pressure). On April 4, 2016, these transducers began giving erroneous values, causing the Built-In Test (BIT) firmware to shut down the MCA. Analysis of telemetry data indicated that an Operational Amplifier (OpAmp) on a circuit card in ORU 01 Q0001 failed. At that time, ORU 01 Q0001 had been operating nearly continuously for fifteen years.

On April 7, 2016, ORU 01 Q0001 was replaced by ORU 01 F0001. After power up, the pressure transducer readings returned to expected values, confirming that the problem was in the ORU 01 electronics and not in the pressure transducers themselves. The new ORU 01 has a newer version of firmware, version 4.25, than the replaced ORU 01, which had version 4.18. The performance of the MCA with this new firmware has been nominal, as previously described.

ORU 01 Q0001 has been returned to earth and is in the process of repair at UTAS Pomona. Even without failure of the OpAmp, the program expected this ORU 01 to need to be returned for service, since the non-volatile memory that holds the firmware is rated by the manufacturer for ten years, and it had already been approximately 15 years since the firmware was programmed into the EEPROM. In addition to the repair of the OpAmp, the non-volatile memory will be refreshed.

X. Conclusion

The MCA in the Lab supplies the ISS with reliable, stable partial pressure measurements for the major constituents of the ISS atmosphere. The Node 3 MCA is in the process of stabilization. This is the first time that two fully operational MCAs have been operated simultaneously. Once sufficient data become available, comparative evaluation of the two MCAs can be made.

References

- ¹Gardner, B. D., Erwin, P. M., Chladek, R., and Matty, C., "International Space Station Major Constituent Analyzer On-orbit Performance," *46th International Conference on Environmental Systems*, Vienna, Austria, 2016.
- ²Gardner, B. D., Erwin, P. M., Thoresen, S. M., Wiedemann, R. and Matty, C., "International Space Station Major Constituent Analyzer On-orbit Performance," *45th International Conference on Environmental Systems*, Bellevue, WA, 2015.
- ³Gardner, B. D., Erwin, P. M., Thoresen, S. M., Granahan, J. and Matty, C., "International Space Station Major Constituent Analyzer On-orbit Performance," *42nd International Conference on Environmental Systems*, San Diego, CA, 2012.
- ⁴Gardner, B. D., Erwin, P. M., Thoresen, S. M., Granahan, J. and Matty, C., "International Space Station Major Constituent Analyzer On-orbit Performance," *40th International Conference on Environmental Systems*, Barcelona, Spain, 2010.
- ⁵Gardner, B. D., Erwin, P. M., Lee, W. T., Tissandier, A. M. and Thoresen, S. M., "Improving the Measurement Accuracy of Water Partial Pressure Using the Major Constituent Analyzer," *39th International Conference on Environmental Systems*, Savannah, GA 2009.
- ⁶Thoresen, S. M., Steiner, G. and Granahan, J., "International Space Station (ISS) Major Constituent Analyzer (MCA) On-orbit Performance," *38th International Conference on Environmental Systems*, San Francisco, CA 2008.